Internal Pipe Inspection Robot

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Abstract

This paper describes a new mechanism, communication system, and vision system of an internal pipe inspection robot. To date, inspection robots have had such limitations as their mobility to turn in a T-shaped pipe or move in a plug valve. The new mechanism based on our dual magnetic wheels, resembling a crawler, not only overcomes the limitation but enables the robot to climb over sharp obstacles like sleeve and dresser joints. Another drawback of earlier robots is that the friction between the pipe and the cables for communication and power supply makes it difficult to move a long distance. A fiberoptic communication system can reduce the friction.

The new vision system has been significantly miniaturized, enabling it to clearly view and inspect the welded section underneath the robot while gazing ahead for navigation.

An experimental inspection robot has been successfully made to confirm the efficiency of the new mechanism, communication system, and the vision system.

1 Introduction

Buried pipes, commonly used for gas conduits, cannot be inspected as efficiently as above-ground pipes because of the excavation and backfilling work involved. In other words, the ground must be excavated prior to inspection to expose all sides of underground pipes laid at a depth of at least one meter, and then earth must be backfilled after the inspection is completed in order to return the area to its original condition. All this work takes a significant amount of time beyond the time required for the actual inspection.

Inspection procedures for underground structures [1] have improved the efficiency of the excavation work. A thorough understanding of the current status underground is obtained first to allow high-speed excavation to the target pipe while avoiding other underground items. This procedure would be adequate if improving excavation speed was all that was needed, but it does not reduce excavation time enough. What is needed is a review of the exteriour surface inspection method itself. In addition to outer surface inspection, another procedure currently in practice is interior surface inspection. Interior surface inspections require excavating a pit just large enough to insert the inspection equipment, so the work can be performed much more efficiently in terms of both cost and time. Since most pipes are laid under roads, this procedure offers the general public the advantages that less excavation means that less road surface area torn up and time needed for the work, and neither pedestrian nor vehicular detours are necessary.

Interior surface inspection technology, such as the remote field eddy current inspection [2], has been established to check the status of corrosion in pipes. An effective repair method known as the live-joint-seal process [3] as well as in-pipe welding robots [4] have also been industrialized. As you can see, the basic technologies for interior pipe inspections and repair are rapidly being developed.

One of the problems with interior surface inspections is the inadequate performance of the robot device that moves inside the pipe from the insertion pit to the inspection site. Various mechanisms [5]-[7] have been proposed to date for robots traveling inside pipes, and several have actually reached a practical level. Unfortunately, robots to iron pipes with diameters ranging from 150 mm to 600 mm would pose the following problems.

Problem 1 Robots occupies most of the cross section of the pipe

Objects protruding into pipes, such as plug valves, are difficult to negotiate for robots. Robots also cannot move through pipes of different diameters connected by means of reducers (particularly from larger to smaller diameter pipes), or pass through narrow paths, such as valve locations.

Problem 2 Robots cannot negotiate pipe bends.

Robots are equipped with a mechanism that will turn the robot naturally to cope with bends when traveling through an

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L-shaped pipe. Therefore, the robots cannot turn directly into a T-shaped pipe because they cannot bend into the pipe. This is a significant restriction since T-shaped pipes are often used underground.

Problem 3 The travel distance is short.

The frictional resistance of the communication and power cables along the pipe increases, so the distance traveled is limeted to approximately 100 meters. The friciton is particularly great in the L section of L-shaped pipes, so the distance traveled is even shorter as the number of Ls encountered in L-shaped pipes increases.

Problem 4 The gas supply is shut off for gas conduits.

Restrictions, such as robot shape and cable use, mean that the pipe must be disconnected for robot insertion and inspection. The disconnection not only forces a gas supply shutoff in that area, but also poses the possiblity of explosions because the interior of the pipe is exposed to outside air. This means that gas in the entire area affected by the pipe cutting must be replaced with a non-flammable gas like nitrogen before the robot is inserted. The work involved poses a significant problem in terms of both time and cost. During robot travel, moreover, the size of cross-sectional areas pointed out in **Problem 1** would incur a pressure drop in the gas supply pressure due to the rapid contraction and enlargement of pipe cross-sections even if the pipes were connected.

These problems increase the cost of interior surface inspections, and thus make such inspections applicable only in limited cases. A robot that can overcome these problems, especially can inspect for at least 500 meters per day on inspection tours, is highly desirable. Here we will report on the concept of just such an internal pipe inspection robot for 150 mm to 600 mm iron piping, as well as on the prototype that was developed. The reason that we limited the inspection to iron piping is that this was the most commonly used for underground pipe laying. Many iron pipes laid before 1965 are still in use, and these are the ones most in need of inspection.

2 Basic concept : Dual magnetic wheel

We conducted studies on the principles of optimum mobile mechanisms in order to overcome the problems outlined above. First we derived a moving speed of 3 ~ 5 meters per minute from the travel distance, 2 * 500 meters, and work time, eight hours including inspection, and then determined that worm-type and walking-type robots could not possibly meet this stipulation. For these reasons, it was clear that we needed a wheeled-type mobile mechanism. However, a simple wheeled robot would have difficulty navigating vertical pipes. A wheeled robot equipped with springs or magnets could cope with vertical pipes. Because the use of springs would greatly increase the pipe cross-sectional area occupied, it would be difficult to resolve **Problem 1**. Moreover the ordinary spring-wheeled robot can not overcome **Problem 2**. In contrast, the use of magnets is limited to iron and similar pipes because of the basic property of magnets, but the lower cross-sectional area would resolve **Problem 1** and the method of movement shown in Fig. 1 would overcome **Problem 2** without complex mechanisms and controls. For these reasons, we settled on a magnetic wheel-type mechanism basically.

Unfortunately, another difficulty is that there are multiple bumps inside pipes, such as joints, and a significant amount of energy is required to negotiate these with ordinary magnetic wheels. In general, crawler-type mechanisms are the most effective means of dealing with the bumps, but these require so many wheels that the mechanism could not navigate L- and

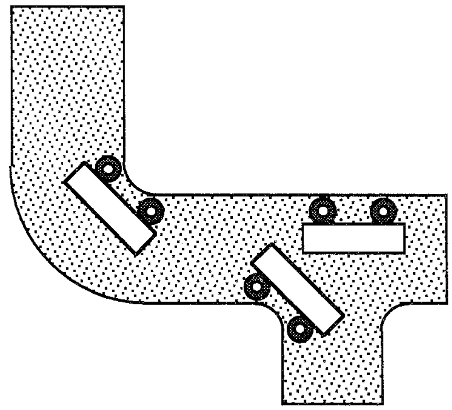

Fig. 1 Magnetic Wheel Robot

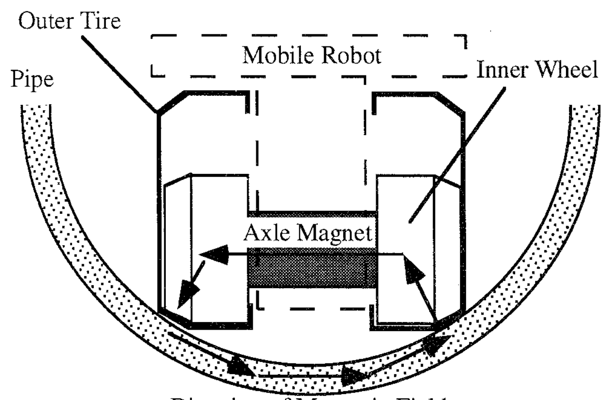

Fig. 2 Magnetic Wheel Concept

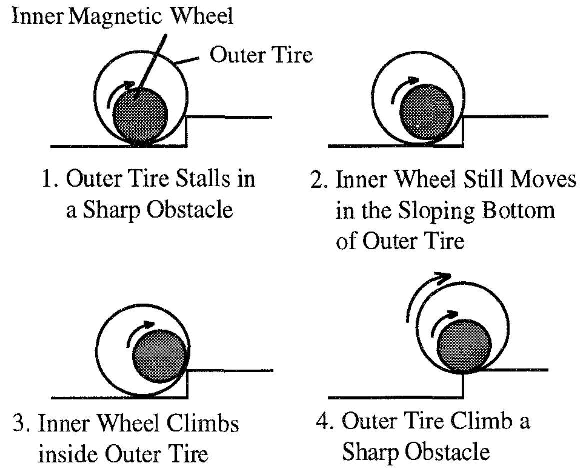

Fig. 3 Magnetic Wheels Climb a Sharp Obstacle

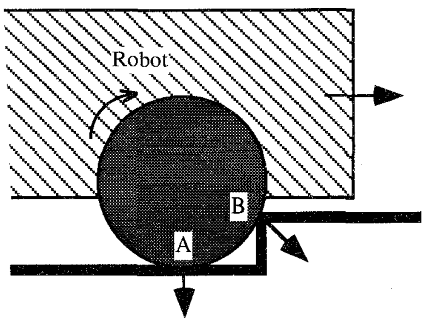

Fig. 4 Problem of Ordinary Magnetic Wheel

T-shaped pipes. For this reason we decided against a crawler-type mechanism, and focused on developing the dual magnetic wheel concept [8]. Here we formed a magnet into an axle to which outer tires and magnetic inner wheels as shown in Fig. 2 are attached. Because we used the magnet as an axle rather than as the inner wheels, the magnet lasts much longer, and a powerful magnetic force is generated because of the closed magnetic circuit formed by the pipe. This dual magnetic wheel allows the robot to travel over bumps which are lower than half the diameter of the outer wheel as shown in Fig. 3. To be more specific, the subject of the ordinary magnetic wheel mechanisms are shown in Fig. 4. There are two suction forces at point A and B and the suction force at point A disturbes the robot to climb a sharp obstacle. It can be resolved because the inner wheel can climb even inside the locked outer tire in Fig. 3-1. Rust, which is a problem with ordinary magnetic wheels, is easily removed by wheel rotation when the outer tire moves away from the magnet.

3 Development of a communication control system

An ideal type to overcome **Problem 3** is an autonomous robot that operates without an external power supply or communication cables. First, equipping the robot with a battery can eliminate the need for a power supply cable. However a communication cable must be used. It is possible to eliminate the communication cable if the pipes are straight and the distance the robot travels is less than 100 m[9], which do not satisfy the specification of the robot. On the other hand, a conventional communication cable causes the voltage drop of the cable which limits the travel distance.

Therefore a communication control system using fiberoptic cable with a battery is developed. The fiberoptic cable resolved the voltage drop problem, and because the cable is so thin, it can be wrapped on a roller on the side of the robot. This not only eliminates cable traction, but it also removes restrictions on the distance traveled caused by friction between the cable and the pipe. In short, constant tension on the cable is effectively eliminated because rotation of the roller feeds out the cable during forward motion, and similarly rewinds the cable during reverse motion. In this case, O/E converter for signal reception, controller, camera control unit, and E/O converter for image output transmission in Fig. 5 mounted on the prototype robot.

The optical fiber measures 0.25 mm in diameter, and a spool with an outside diameter of 30 mm and a width of 107 mm wound with a 500-meter cable has an outside diameter of

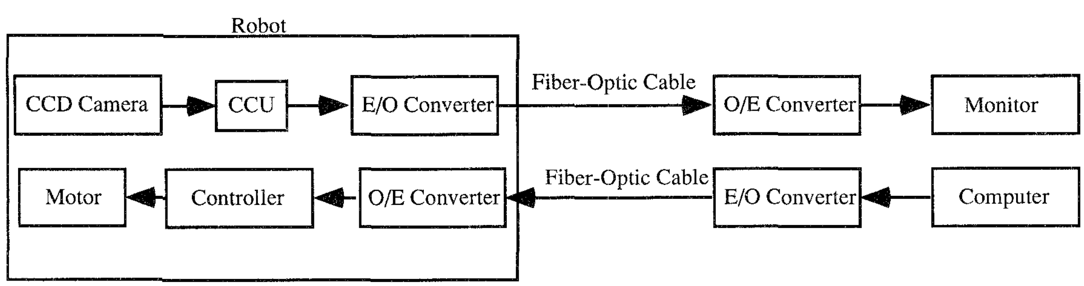

Fig. 5 Configuration of Robot System

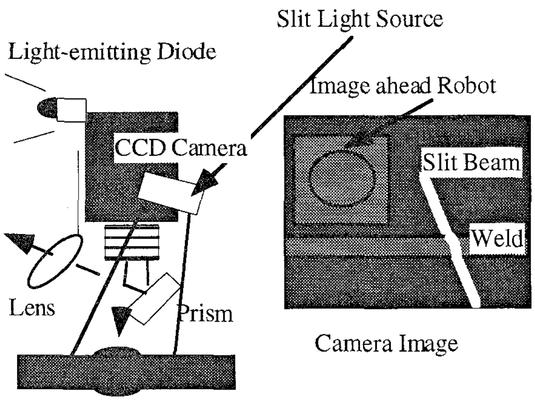

Fig. 6 Compact Visual inspection System

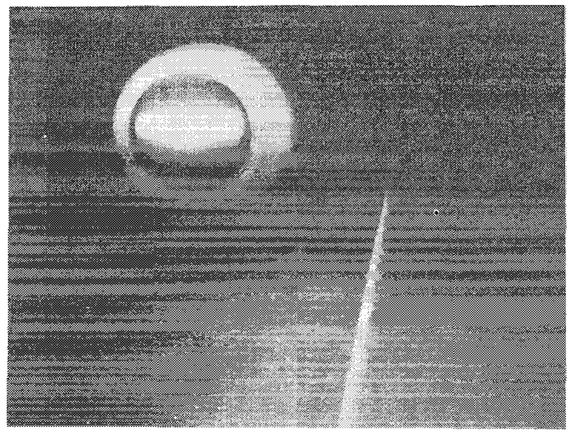

Fig. 8 Actual detected image of a pipe (1)

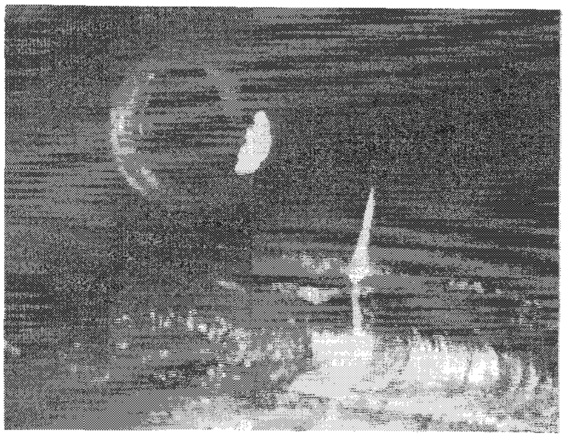

Fig. 7 Actual detected image of a pipe with welded section

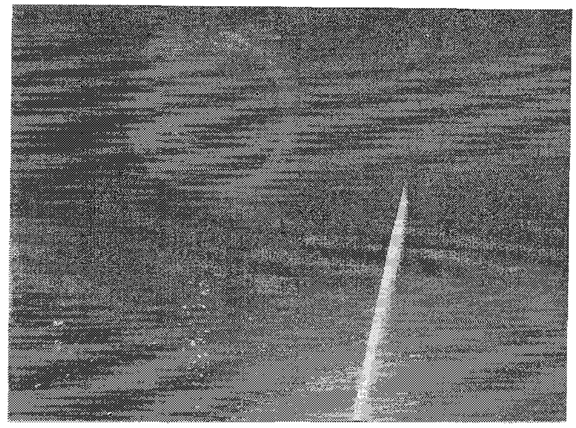

Fig. 9 Actual detected image of a pipe (2)

36 mm, so it can be coiled on the robot with no problem. Since the minimum bend radius of the cable is 5 mm, the effects of winding are virtually nil. Signal attenuation is less than 10% with a 500-meter cable if the wound diameter of the cable is at least 20 mm, so attenuation is not a problem in practice.

4 Compact visual inspection system

We developed a compact visual inspection system for the robot to inspect welded sections[10]. Because of size limitations, placing one camera on the robot for forward observation during travel and another for inspection of welded sections is not at all desirable. Therefore, we developed a device that can observe two directions with one camera by installing the camera facing downward and a prism mirror for the forward direction as shown in Fig. 6. The reason that the camera faces downward is that the more detailed images are required for inspections than for viewing the relatively simple forward direction. The main problem here was adjusting the focus. In contrast to the four centimeter focal length required to view welded sections in the downward direction, 30 cm was required in the forward direction to recognize pipe status, such as T- and L-shaped pipes, for example. Therefore, we first focused the camera in the downward direction, and then adjusted the focus in the forward direction by a non-spherical lens. The weld line is illuminated with a slit light formed with light-emitting diodes and a cylindrical lens. Two other light-emitting diodes provide illumination in the forward direction. We used light-emitting diodes here because they are a very light load on the battery.

Figs. 7, 8, and 9 show actual detected images. Fig. 7 is a

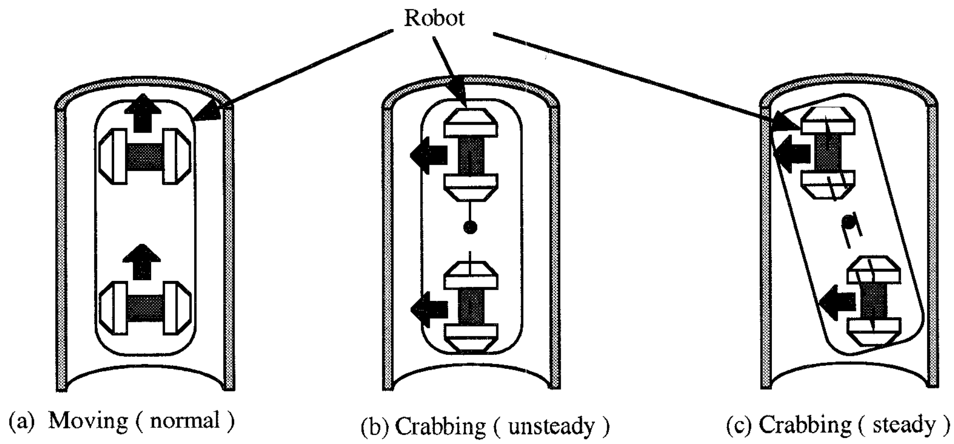

Fig. 10 Crabbing for Inspection

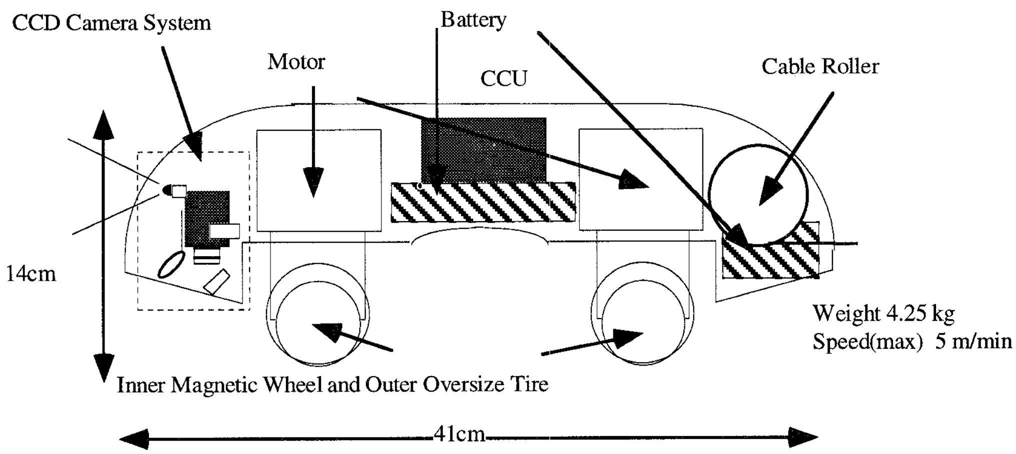

Fig. 11 Conceptual Configuration of Prototype

scan that clearly shows the excellent condition of the welded sectionis and straight piping lies ahead in the forward direction. Figs. 8 and 9 are images from travel in an ordinary pipe. In Fig. 8, the pipe in the forward is a T-shaped pipe measuring 150 mm in diameter. The reflection of the center is peculiarity of the T-shaped pipe. Fig. 9 shows a L-shaped pipe measuring 200 mm in diameter. The right side of the reflection becoming dim indicates that the L-shaped pipe is turning right. In this system, the images are not clearly influenced by the diameters of the pipe.

With the inspection device, the robot must follow the weld line in order to inspect the full circumference of the line. Basically this is made possible by rotating the robot wheels 90° as shown from Figs. 10 (a) to (b) and climbing in the pipe. Unfortunately, the position of the robot as shown Fig. 10 (b) is not so steady in terms of vibrations and acceleration. To overcome this problem, the robot body is angled as shown in Fig. 10 (c) for a more steady posture that allows travel in the circumferential direction.

5 Development of the prototype

A prototype has been built featuring the newly developed devices described above. Measuring 410 mm long overall, 90 mm wide, and 140 mm height, the robot is able to navigate narrow pathways like valve locations and can negotiate obstacles like plug valves. The bottom as well as the front and rear sections of the robot are cut down as shown in Figs. 11 and 12 in order for it to travel through L-shaped pipes measuring 150 mm in diameter. The robot weighs 4.25 kilograms and provides a stable travel range even on the ceiling because the suction force of the dual magnetic wheel is 30 kilograms/wheel. A suction force of 7 kilograms/ wheel in 2-mm increments makes the robot travel even when

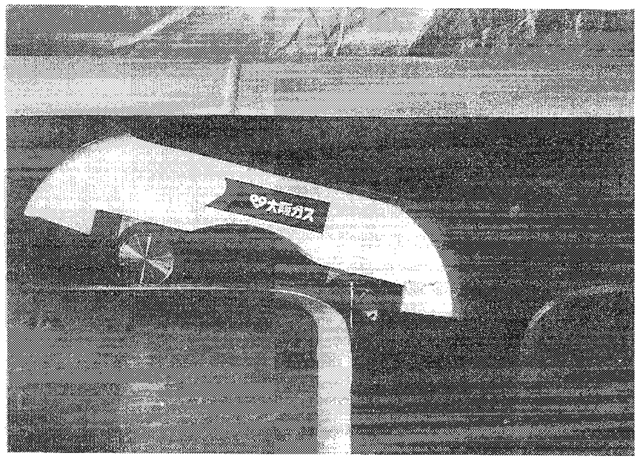

Fig. 12 Picture of Prototype

gaps occur due to rust, dust and other disturbances.

The 8.4 volt by 1.5 amp (Normal) or the 16.8 volt by 3.0 amp (Turbo) battery modes supply enough power for steering and for the drive motors. The sum traction forces of the two wheels for the battery modes are 1.8 kgf and 5.1 kgf, respectively, the torque of a drive-wheel is 2.3 kg-cm and 6.4 kg-cm, respectively, and the maximum travel speed is 3 m/min and 5 m/min, respectively. For efficiency, the Turbo mode is used only when that level of torque is needed, such as for bumps and travel up vertical piping.

Because basic controls are provided by the control circuit featured in the robot, a personal computer (33-MHz IBM-PC and 33-MHz NEC-PC-98 Note tested) is all that is needed to provide 10 different external instruction via pulse width modulation which is relative immunity to noise. These instructions include front and rear wheel speed, angular speed, lighting, Turbo/Normal switching, and roller winding. Each pulse may take any value between 0.8 and 2.0 ms and the pulse series are separeted by a long gap, 20 ms, to indicate the start of a new series. These values are appropriate for this robot. Control signals generated by the external computer are transmitted to the robot through the E/O converter. For this robot the above-ground facility comprises just a notebook-type personal computer, an O/E converter, an E/O converter and a TV monitor, which are easily transported.

6 Conclusion

This thesis proposed a dual magnetic wheel robot for in-pipe travel, and confirmed the efficacy of such a robot with an actual model. Through a combination of the dual magnetic wheel and fiberoptic communication, the robot overcomes the problem areas found in conventional in-pipe traveling robots. The robot is all the more practical because it features a newly developed miniature device for the visual inspection of welded section.

In this paper, **Problem 4** is not investigated. This dual magnetic wheel robot resolves **Problem 1** and **Problem 3**, that means the pipe can be connected during the insertion. Some equipments for insertion have been established and it is not difficult to develop an equipment for this robot insertion.

The next step in terms of software will be to automate recognition, inspections and control, and in hardware will be to conduct studies on the durability and multi-vehicle coupling to provide multi-task robots.

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